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Perception of better nasal patency correlates with increases in mucosal cooling after surgery for nasal obstruction

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Abstract

Objectives—1. Quantify mucosal cooling (i.e., heat loss) spatially in the nasal passages of nasal airway obstruction (NAO) patients before and after surgery using computational fluid dynamics (CFD). 2. Correlate mucosal cooling with patient-reported symptoms, as measured by the Nasal Obstruction Symptom Evaluation (NOSE) and a visual analog scale (VAS) for sensation of nasal airflow.

Study Design—Prospective

Setting—Academic tertiary medical center.

Subjects and Methods—Computed tomography (CT) scans and NOSE and VAS surveys were obtained from 10 patients before and after surgery to relieve NAO. Three-dimensional models of each patient's nasal anatomy were used to run steady-state CFD simulations of airflow and heat transfer during inspiration. Heat loss across the nasal vestibule and the entire nasal cavity, and the surface area of mucosa exposed to heat fluxes > 50 W/m^2 were compared pre- and post-operatively.

Results—After surgery, heat loss increased significantly on the pre-operative most obstructed side (p values < 0.0002). A larger surface area of nasal mucosa was exposed to heat fluxes > 50 W/m^2 after surgery. The best correlation between patient-reported and CFD measures of nasal patency was obtained for NOSE against surface area in which heat fluxes > 50 W/m^2 (Pearson r = −0.76).

Conclusion—A significant post-operative increase in mucosal cooling correlates well with patients' perception of better nasal patency after NAO surgery. CFD-derived heat fluxes may prove to be a valuable predictor of success in NAO surgery.

Keywords

nasal obstruction; mucosal cooling; nasal surgery; septoplasty; turbinate reduction; NOSE scale; visual analog score (VAS); heat flux; computational fluid dynamics (CFD)

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Introduction

Nasal airway obstruction (NAO) is a common problem, negatively affecting quality of life for millions, and costing upwards of $5 billion annually in the United States.[1] Causes of NAO are multifactorial. Pharmacologic treatment may be successful, but anatomic abnormalities that require surgical correction are often identified. The decision to proceed to surgery such as septoplasty or inferior turbinate reduction is often based on the surgeon's assessment alone without the use of objective testing. However, NAO surgeries have reported failure rates ranging from 23 to 37 percent.[2–7]

Multiple studies have found no significant correlation between subjective and objective measures of nasal patency.[7–10] One reason proposed for this incongruity is that objective tests may be measuring the wrong variable. Commonly used tests such as rhinomanometry, peak nasal inspiratory airflow, and acoustic rhinometry focus on resistance as a measure of patency.[10–15] However, a growing body of literature suggests that it is the change in temperature of the nasal mucosa, not resistance, that signals nasal patency.[16–23] Measuring intranasal temperature changes may not be practical in a clinical setting but computational fluid dynamics (CFD) models can simulate this physiological process.[9,24–28]

CFD can be used to simulate airflow through three-dimensional (3D) reconstructions of the nasal cavity, providing detailed physiological variables, including "heat flux," which measures heat loss from the nasal mucosa to inspired air, and thus is a proxy to changes in nasal wall temperature. Previous CFD studies have computed heat fluxes in the nasal mucosa and found they compare favorably with in vivo measurements of nasal wall temperature.[25] However, to the best of our knowledge, only two studies have attempted to correlate simulated heat flux to the sensation of nasal patency.[9,29]

This article presents results of a prospective study designed to correlate the subjective feeling of nasal obstruction with CFD-derived objective measures.[29–31] We recently reported that post-surgical relief of nasal obstruction correlates with changes in several CFD variables (nasal resistance, airflow, heat flux, and shear stress).[31] The present manuscript is aimed at performing a more in-depth analysis of the role of mucosal cooling in nasal obstruction. In particular, we investigate how nasal surgery affects the spatial distribution of heat fluxes on the nasal mucosa. More importantly, this paper investigates (1) whether the correlation between mucosal cooling and patient-reported measures is affected by the anatomic location of heat loss (nasal vestibule vs. entire nasal cavity) and (2) whether the perception of nasal airflow is due to a localized stimulation (peak heat flux) or a more uniform stimulation throughout the nasal cavity.

Methods

PATIENT RECRUITMENT AND TREATMENT

Research methods were approved by the institutional review board at the Medical College of Wisconsin, and written informed consent was obtained. To be enrolled in this study, patients had to be at least 16 years old, have a diagnosis of anatomic nasal obstruction (deviated septum, turbinate hypertrophy resistant to medical treatment, or nasal valve collapse), and elected to have surgery. Patients with nasal obstruction primarily due to rhinitis, sinusitis, neoplastic, or autoimmune processes (i.e. not due to anatomically-based etiology) were excluded. Surgical treatment decisions were made by the surgeon (J.S.R.) based on the clinical presentation and standard of medical care (Table 1). Standard postoperative care was performed and recovery and healing were uneventful for all patients.

Forty (40) patients with NAO were recruited between July/2009 and June/2012. Axial computed tomography (CT) of the entire nasal cavity and external nose was performed before and 3–9 months after surgery with 0.6-mm increments and 0.313-mm resolution. There was no attempt to control for the nasal cycle, thus many patients exhibited pronounced pre to post-surgery changes in nasal anatomy that were physiologic variations unrelated to surgery. Eliminating the confounding effects of the nasal cycle is beyond the scope of this manuscript and is the objective of a future paper. Thus, we selected for this study a subgroup of 10 patients with no obvious changes in turbinate thickness due to the nasal cycle between pre- and post-operative CT scans. This selection process was by visual inspection alone; no strict criteria (such as anatomical measurements) were applied, thus only patients with obvious nasal cycling were excluded. To avoid bias, the first 10 patients matching this criterion were selected.

MODELING AND SIMULATION

Pre- and post-surgery CT scans were used to create digital 3D models of each patient's nasal cavity (excluding the paranasal sinuses) using Mimics 14.0 (Materialise, Plymouth, MI). Pre- and post-surgery models were coregistered using 3D reconstructions of the patient's skull. Our CFD modeling methods have been described in detail elsewhere.[26,29] Briefly, planar nostril and outlet surfaces were created, and the digital models were meshed with approximately 4 million tetrahedral cells using ICEM-CFD 14.0 (ANSYS, Inc., Canonsburg, PA). Steady-state inspiratory airflow simulations were conducted in Fluent 14.0 (ANSYS Inc) with the boundary conditions: (1) air velocity set to zero at stationary walls, (2) pressure-inlet at the nostrils with gauge pressure set to zero, and (3) a pressure-outlet condition such that the pressure drop from nostrils to choana was the same in pre- and post-surgery models. This transnasal pressure drop reproduced the inhalation rate expected for each patient's body mass (see below) post-operatively. In other words, inhalation rates were different before and after surgery depending on nasal resistance and body mass, while the same pressure drop was used pre- and post-surgery so that the inhalation rate had its expected value post-operatively.

The expected minute volume for humans of different sizes can be estimated based on gender-specific power law curves: [32]

$$\begin{array}{ll} \text{Males (sitting awake):} & \dot{V}_E = (1.36 \pm 0.10) M^{0.44 \pm 0.02} \\ \text{Females (sitting awake):} & \dot{V}_E = (1.89 \pm 0.40) M^{0.32 \pm 0.06} \end{array}$$

where $\dot{V}_E$ is the minute volume in liters per minute (L/min) and M is the body mass in kilograms (kg). The steady-state inhalation rate used in the simulations is twice the minute volume of each patient. Values used for the density and dynamic viscosity of air were 1.204 kg/m^3 and 1.825×10^{-5} kg/(m.s), respectively. For heat transfer simulations, the nasal mucosa temperature during inspiration was set to 32.6°C.[26,33] Heat flux, which is the rate of heat transfer across a surface per unit time and area (units of W/m^2), was calculated as $\vec{\Phi} = k\nabla T$, where $k = 0.0268$ W/(m.K) is the specific heat of air and ∇T is the temperature gradient at the wall. Heat transfer rate (units of W) is the total amount of heat crossing a surface per unit time. Fluent and Fieldview 13.2 (Intelligent Light, Rutherford, NJ) were used to analyze simulation results.

OUTCOME MEASURES

Outcome measures calculated by CFD include: (1) heat transfer rate for the entire nasal cavity with the choana as the posterior boundary; (2) heat transfer rate across the nasal vestibule; (3) surface area of nasal mucosa where heat flux exceeds a stimulation threshold; (4) heat fluxes averaged along the perimeter of coronal cross-sections and plotted as a function of distance from the nostrils; and (5) peak heat fluxes, defined as the value above which only 1 cm^2 of mucosa is exposed to. To compute the distance from the nostrils, the most posterior edge of the nostrils was defined as origin of our coordinate system (Figure 1). The nasal vestibule was defined posteriorly by the piriform aperture and superiorly by a plane that crossed a notch into the nasal cavity (Figure 1). More specifically, the posterior boundary of the vestibule was located 3.4 ± 1.2 mm from the origin, while the superior boundary was located 15.0 ± 2.0 mm above the origin.

Patients were administered the Nasal Obstruction Symptom Evaluation (NOSE) to collect information on patient-reported symptoms before and after surgery.[34] The NOSE scale is a disease-specific quality-of-life instrument for NAO that has been validated for septoplasty and nasal valve repair, and is used to measure surgical success.[35] The NOSE scale was selected because (a) it is simple and quick, (b) it is the quality-of-life (QOL) instrument most frequently used to assess surgical outcomes in NAO, and (c) it is more specific for NAO than other rhinological QOL instruments.[36,37] It is a five item scale where each patient scores, over the past month, their symptoms of nasal congestion, nasal blockage, trouble breathing through the nose, trouble sleeping, and air hunger sensation using a scale from 0 (not a problem) to 4 (severe problem). These numbers are summed and multiplied by 5 to give a score that ranges from 0 – 100.

Finally, unilateral visual analog scale (VAS) scores for nasal airflow were collected before and after surgery. Patients were asked to cover one nostril and rate their ability to breathe through the uncovered nostril on a scale of 0 (completely obstructed) to 10 (no obstruction). The VAS score was a subjective measure of instantaneous airflow at the time of consultation, while the NOSE score was used to assess the symptoms of nasal obstruction during the past month.

STATISTICAL ANALYSIS

Two-tailed paired Students t-tests were used to test the hypothesis that post-operative values were statistically different from pre-operative values. Differences were considered statistically significant for p-values < 0.05. The correlation coefficients between subjective and objective measures (Table 2) were computed using Pearson's correlation coefficient, while the trendlines were obtained by a least-squares linear regression.

Results

Symptoms of nasal obstruction subsided after surgery as shown by improvement in NOSE and VAS scores. NOSE scores decreased from 74 ± 18 pre-surgery to 25 ± 24 post-surgery (p = 0.0006), while VAS scores increased from 3.0 ± 1.1 pre-surgery to 7.3 ± 2.6 post-surgery in the most obstructed side (p = 0.001). VAS scores in the less obstructed side were not significantly affected by surgery (7.1 ± 1.9 pre-surgery, 7.8 ± 2.2 post-surgery; p-value = 0.52). Although there was 1 patient whose NOSE score remained the same (65 pre- and post-surgery) and another patient whose VAS score in the most obstructed side got worse (4 pre-surgery, 2 post-surgery), most patients exhibited improvement in NOSE and VAS scores after surgery.

A visual representation of a single patient's heat flux distribution (Figure 2) illustrates notable differences between pre- and post-surgery values. Warmer colors indicate areas of greater heat loss, with red being the highest value. A postsurgical increase in heat flux is observed in the right nasal cavity, which was the most obstructed side in this patient (Figure 2).

The average heat flux over the entire surface area of the nasal cavity (nostrils to choana) and over the vestibule had statistically significant differences pre- to post-surgery in the most obstructed side ($p < 0.0002$) (Figure 3). The heat fluxes in the less obstructed side were not affected by surgery (Figure 3). It is noteworthy that heat fluxes are significantly higher in the vestibule than in the nasal cavity as a whole because inhaled air is warmed as it flows through the nasal cavity, so that the burden of warming inspired air belongs mostly to the anterior nose (Figure 3).

When heat flux is plotted as a function of distance from the nostrils, a peak in heat flux is found in the nasal vestibule, followed by a consistent decline the more posteriorly we move from the nostrils (Figure 4). A statistically significant increase in heat flux is observed post-operatively around the vestibule as well as in the posterior nose ($p < 0.05$).

The surface area where heat flux exceeds a stimulation threshold showed significant increase post-operatively in both the entire nasal cavity and in the vestibule on the most obstructed side (Figure 5). If we assume arbitrarily that thermo-receptors in the nasal mucosa are stimulated when heat fluxes exceed 250 W/m^2, we conclude that the area of nasal mucosa stimulated by mucosal cooling increased from 15% before surgery to 28% after surgery (Figure 5, left panel).

A plot of NOSE scores versus surface area where heat flux > 50 W/m^2 on the obstructed side showed a general negative trend (Figure 6), with post-operative NOSE scores declining in correlation with a larger area stimulated by mucosal cooling. VAS scores versus the area where heat flux > 50 W/m^2 showed a general positive trend, with higher VAS scores (more patent) correlating with larger area stimulated by mucosal cooling (Figure 6).

Correlations were performed between NOSE and VAS scores and each individual measure of heat loss. NOSE scores had the strongest correlation with the surface area stimulated by heat fluxes > 50 W/m^2 ($r = -0.76$) (Table 2, Figure 6). VAS score also had its strongest correlation with the area stimulated by heat fluxes > 50 W/m^2 with $r = 0.63$. Generally speaking, NOSE scores correlated with heat flux better than VAS scores (Table 2).

Discussion

Objective measures of nasal patency traditionally have focused on nasal resistance and cross-sectional areas, assuming that these would correlate well with patients' perception of nasal obstruction.[10–15] An alternative hypothesis that developed in parallel is that subjective perception of nasal obstruction may correlate better with mucosal cooling, rather than with nasal resistance.[16–23]

The application of a cooling sensation to the nasal mucosa has long been known to give a subjective sense of relief for NAO – mentholated agents as well as inhaled camphor and eucalyptus have been commonplace treatments for nasal congestion for decades. The use of these agents does show a significant correlation between perceived cooling and increased sense of nasal patency without an objective decrease in nasal resistance.[16] These studies led to a broader question of where and how the sensation of nasal flow occurs.

Clarke, Jones, Eccles, and colleagues performed a series of studies investigating the roles of different parts of the nose in sensing nasal patency. Isolated anesthesia of the nasal vestibule produced a well-defined sense of obstruction, whereas topical anesthesia of the respiratory mucosa on the nasal cavum produced a range of sensation changes, but no consistent decrease in nasal patency.[17,20,22] These functional studies are consistent with anatomic studies showing that the density of thermoreceptors is higher in the vestibule than in the cavum.[18,38] These studies suggested that further research of nasal patency sensation should focus on differences between these two anatomically distinct areas.

A series of studies followed, using jets of air at different sites in the nasal cavity, and at different temperatures, to measure thresholds for stimulation. All studies suggest lower stimulation threshold for the vestibule, and an anterior-to-posterior gradation of sensation favoring the vestibule. The importance of the vestibule for sensation was also corroborated in a study by Willatt and Jones.[39] who used an infrared thermometer to measure the temperature of the vestibule on inspiration and expiration and found an increased sense of nasal patency with cooling, and the greater the cooling, the more profound the sense of patency. The current challenge is how this translates to the clinical patient with nasal obstruction.

Intuitively, the physics of airflow and heat exchange suggest that increased nasal resistance is accompanied by decreased flow and reduced mucosal cooling. Lindeman et al.[40] showed this inverse relationship between mucosal cooling and nasal resistance. Zhao et al.[8] found an increased sense of nasal patency when breathing dry vs. humid air, independent of temperature. This suggested that mucosal cooling (via water evaporation) correlates with the perception of patency rather than air temperature alone.

Our data show that mucosal cooling correlates with subjective nasal patency in pre and post-operative NAO patients (Figure 6 and Table 2). After surgery, heat loss increased consistently and significantly on the most obstructed side. As expected based on previous studies of nasal temperature,[24,26] heat fluxes were greatest in the vestibule and gradually decreased further into the nasal cavity (Figure 4). However, post-surgical increases in heat flux were not limited to the vestibule, but showed statistically significant gains both at the vestibule and posterior nasal cavum (Figure 4).

Surprisingly, while both NOSE and VAS scores had good correlations with heat loss in the vestibule of the most obstructed side, this was not the most significant correlation (Table 2), as would have been expected based on previous research suggesting the vestibule is the key anatomical area in subjective sensation of nasal patency.[18,23,41] This unexpected observation may be due to the fact that the total surface area of the nasal cavity (nostrils to choana) is more than 10 times larger than the area of the vestibule (92 ± 15 cm^2 vs. 6.9 ± 1.5 cm^2, measured post-operatively on the obstructed side), so that any differences in thermo-receptor density may be overpowered by the greater surface area of the nasal cavum.

One shortcoming of our study is that rhinomanometry and acoustic rhinometry data were not collected, thus we did not test whether CFD-derived heat flux is more predictive of surgical outcomes than these conventional objective measures. However, a recent study by Zhao and colleagues[9] collected VAS scores, rhinomanometry, acoustic rhinometry, and CFD-derived heat fluxes in 22 healthy subjects. They found that "among all the independent variables, only the peak nasal mucosal heat loss posterior to the nasal vestibule correlates significantly to the perceived patency (Pearson $r = -0.46$)." Therefore, their dataset suggests that CFD-derived heat fluxes may be more predictive of subjective nasal patency than rhinomanometry or acoustic rhinometry.

Interestingly, Zhao and coworkers found a correlation coefficient ($r = -0.46$) between VAS and peak heat flux that is very similar to our correlation coefficient ($r = -0.44$) between NOSE and peak heat flux, but stronger than our correlation ($r = 0.19$) between VAS and peak heat flux. (The inverse sign in our VAS correlation is due to the fact that our VAS scale is inversed as compared to theirs, which considered 0 as completely clear and 10 as completely blocked.) Zhao and coworkers state that CT scans (on which the CFD models are based) were obtained immediately after data collection, which was not the case in our study.

Therefore, their higher VAS correlation highlights the importance of acquiring the images shortly after collecting VAS scores to minimize the confounding effects of the nasal cycle. On the other hand, our stronger correlation between NOSE scores and the area stimulated by heat fluxes ($r = -0.76$) suggests that the best predictor of nasal patency perception may be the surface area stimulated by mucosal cooling, rather than peak heat fluxes.

The ultimate goal of comparing CFD variables and subjective measures is to find a means of judging, based on pre-surgical anatomy, virtual surgery, and CFD modeling, what surgical interventions will most benefit a patient.[30,42–44] The data presented here suggest that CFD may indeed provide nasal physiology variables that correlate with patients' symptoms. However, it is likely that heat flux will not be the sole determinant, but rather the best indication of success may be a combination of variables, such as heat flux, nasal resistance, and wall shear stress. Future research should address this question.

In summary, heat flux (a CFD measure of mucosal cooling) shows clear and statistically significant correlations with subjective patency measures in our cohort, as strong as or stronger than previously tested variables of nasal resistance and wall shear.[31] Our results are in agreement with previous research supporting mucosal cooling as a means of sensing patency.[8,9,16]

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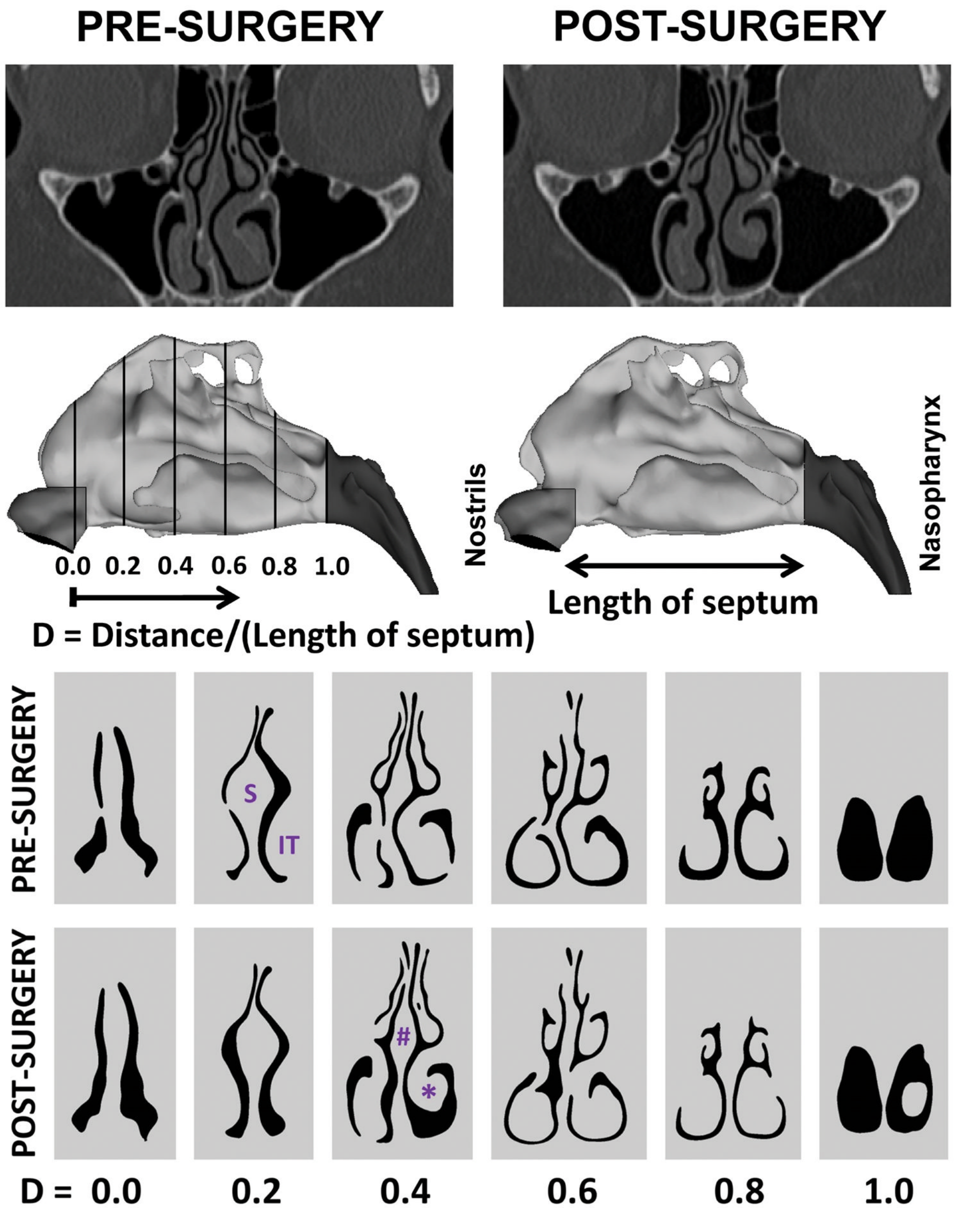

Figure 1.

(Top) Pre- and post-surgery CT scans and computational models of the nasal anatomy of a patient with nasal obstruction. Dark gray: nasopharynx. Light gray: nasal cavity. Middle-tone gray: nasal vestibule. (Bottom) Cross-sections by distance from nostris. Abbreviations: S = septum; IT = inferior turbinate; # = septoplasty; * = turbinate reduction.

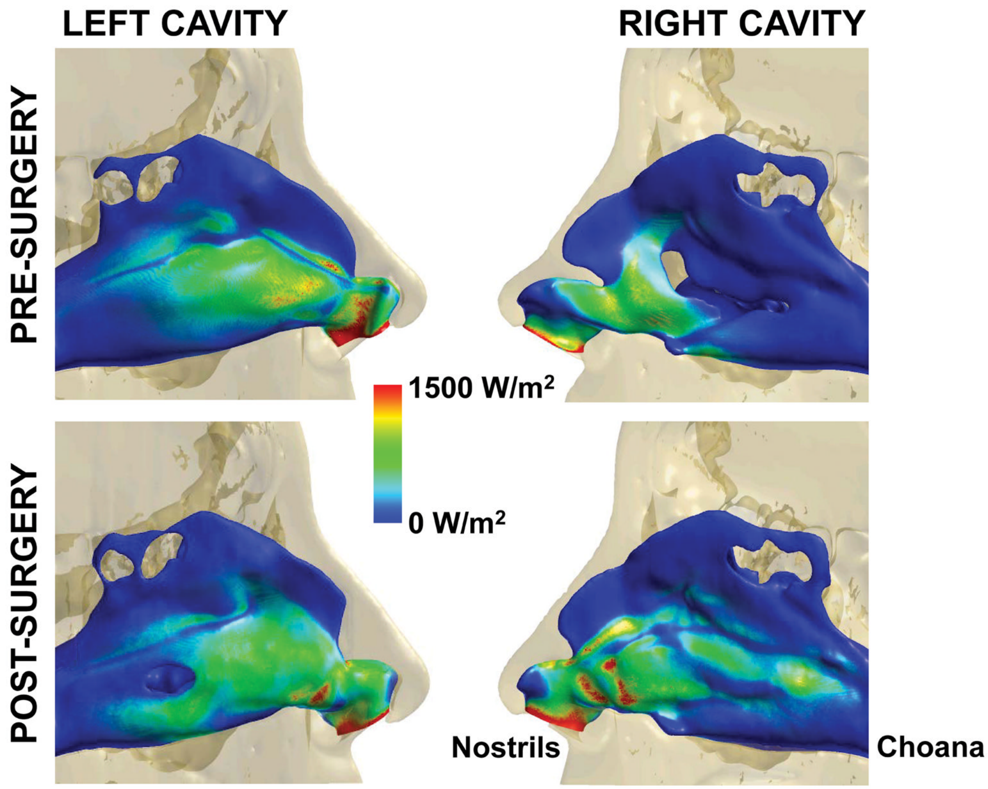

Figure 2.

Spatial distribution of heat fluxes on nasal septum of a patient with nasal obstruction. Post-surgical increases in heat fluxes are noticeable on the right cavity, which was the most obstructed side pre-operatively.

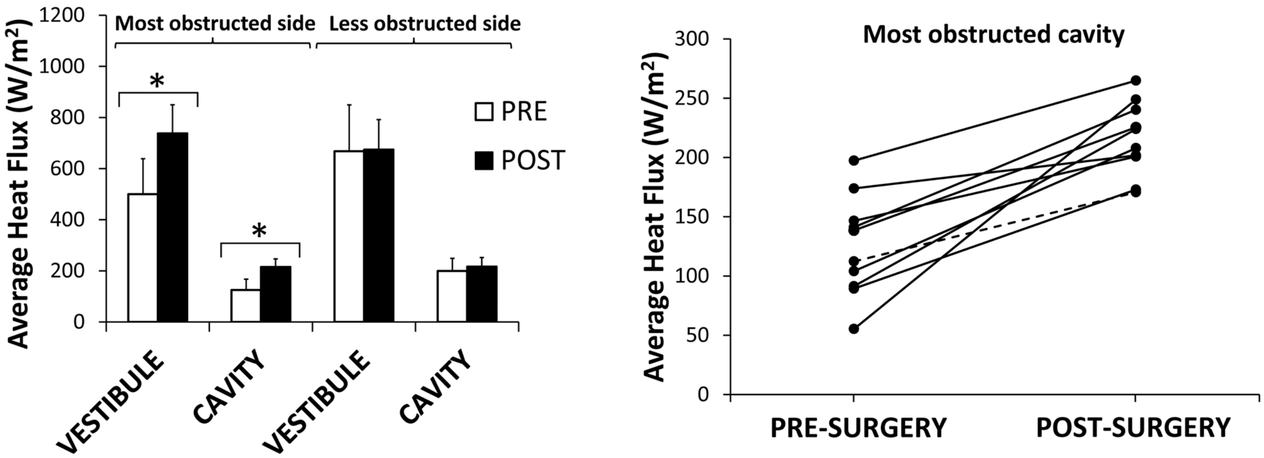

Figure 3.

Average heat fluxes, which are higher in the vestibule than in the nasal cavity, increased post-operatively in the most obstructed side. Asterisks denote statistically significant differences (p-value < 0.0002, $n = 10$ individuals). Highlighted as dashed line is the patient depicted in Figures 1 and 2.

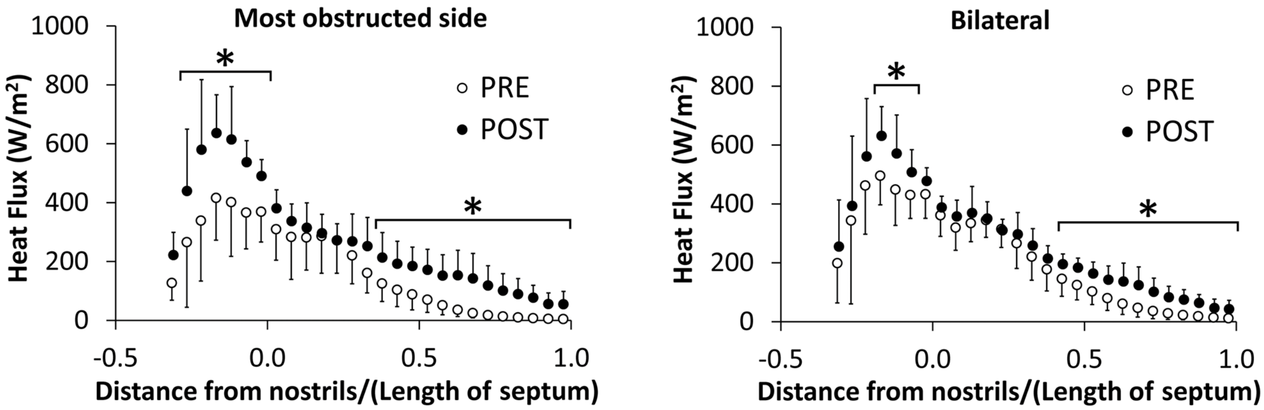

Figure 4.
Heat flux averaged along the perimeter of coronal sections and plotted as a function of distance from nostrils. Asterisks (*) denote statistically higher heat fluxes post-surgery (p-value < 0.05, n = 10 individuals).

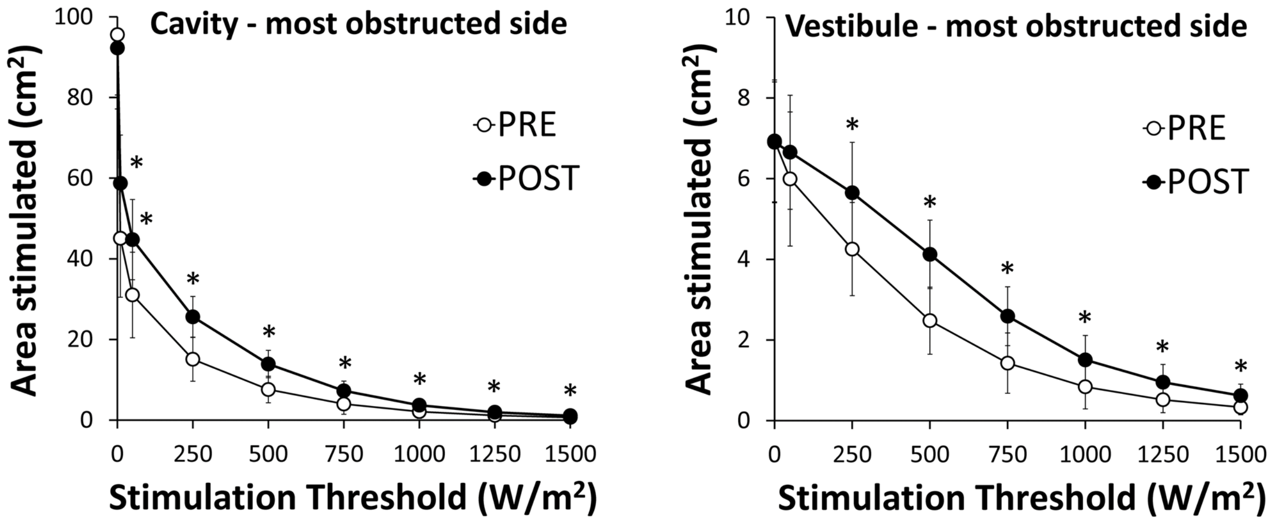

Figure 5.

Surface area stimulated by different levels of heat flux in the nasal cavity (left) and vestibule (right) on the side most obstructed pre-operatively. Asterisks (*) denote statistically higher area post-surgery (p-value < 0.05, n = 10 individuals).

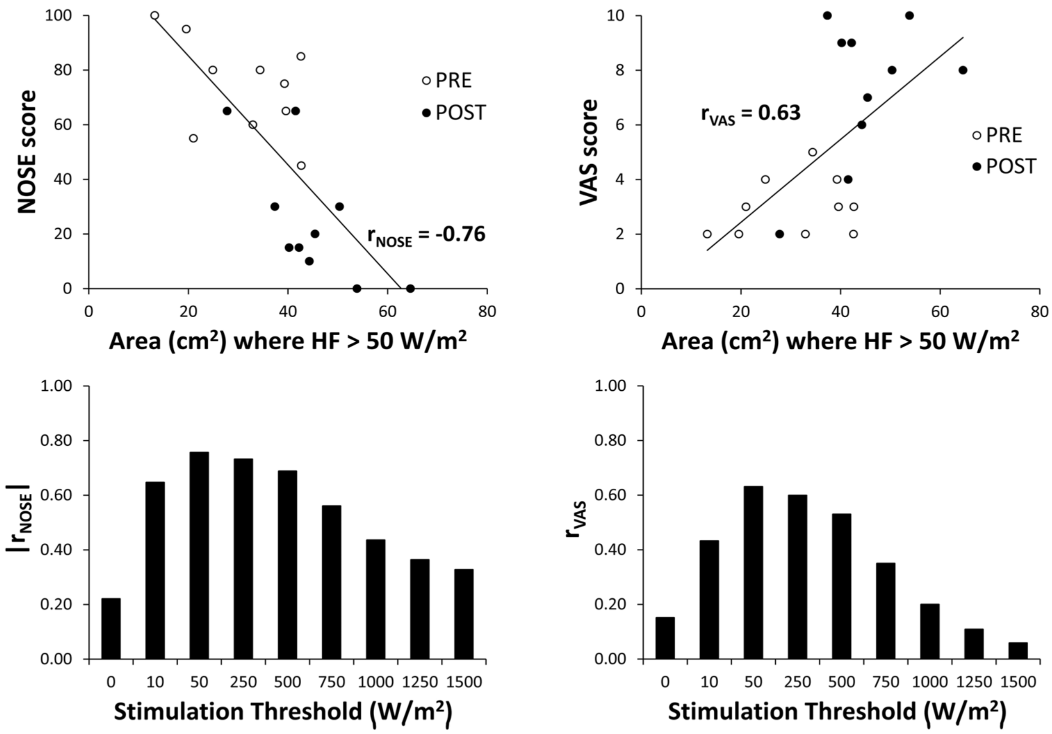

Figure 6.

(TOP) Correlation between subjective measures of nasal patency (NOSE and VAS scores) and the surface area stimulated by heat fluxes (HF) > 50 W/m^2 in the most obstructed nasal cavity. (BOTTOM) The Pearson correlation coefficients for area stimulated vs. NOSE (r_{NOSE}) and VAS (r_{VAS}) are dependent on the heat flux stimulation threshold. The best correlations were obtained for threshold = 50 W/m^2.

Table 1

Surgical procedures to treat nasal obstruction in a cohort of 10 patients.

Patient	Surgery
1	septoplasty, bilateral lateral osteotomies, caudal L-strut
2	septoplasty, left turbinate reduction
3	septoplasty, rhinoplasty
4	septoplasty, left turbinate reduction, bilateral spreader grafts
5	septoplasty, bilateral turbinate reduction, butterfly onlay graft
6	septoplasty, bilateral vestibular stenosis repair
7	septoplasty, right turbinate reduction
8	septoplasty, left turbinate reduction, bilateral spreader grafts
9	septoplasty, bilateral turbinate reduction
10	septoplasty, rhinoplasty, bilateral vestibuloplasty

Table 2

Pearson correlation coefficients (r), 95% Confidence Intervals and p-values between heat loss measures and subjective perception of nasal patency (NOSE and VAS scores). The cohort included pre- and post-surgery data points for 10 patients.

	NOSE		
Variable	**r**	**95% CI**	**p-value**
Heat Transfer Rate across entire obstructed cavity (W)	−0.70	[−0.87, −0.37]	0.0004
Heat Transfer Rate across vestibule in obstructed side (W)	−0.63	[−0.84, −0.25]	0.0024
Area where heat flux > 50 W/m^2 in obstructed cavity (cm^2)	−0.76	[−0.9, −0.47]	<.0001
Peak Heat Flux (W/m^2)	−0.44	[−0.74, −0.00003]	0.05
	VAS		
Variable	r	95% CI	p-value
Heat Transfer Rate across entire obstructed cavity (W)	0.50	[0.08, 0.77]	0.02
Heat Transfer Rate across vestibule in obstructed side (W)	0.39	[−0.06, 0.71]	0.09
Area where heat flux > 50 W/m^2 in obstructed cavity (cm^2)	0.63	[0.26, 0.84]	0.002
Peak Heat Flux (W/m^2)	0.19	[−0.28, 0.58]	0.43